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THE SEASONAL VARIATION OF THE SOIL MOISTURE IN A WALNUT GROVE IN RELATION TO THE HYGROSCOPIC COEFFICIENT

BY

L. D. BATCHELOR AND H. S. REED

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INTRODUCTION

The present investigation was undertaken for the purpose of studying seasonal changes in the soil moisture and their relationship to certain phases of the activity of the trees. The work to be reported is a part of a major study on the 'Winter Injury' or 'Die-Back' of the Persian walnut (*Juglans regia*), certain phases of which were presented in 1919 (Batchelor and Reed[1]). The present publication will present data on the seasonal variations in soil moisture and on various factors which affect soil moisture.

We shall endeavor to show the extreme degree to which orchard soils in semi-arid regions may become desiccated at the end of the growing season, and to point out how this dry condition may persist during winters of light rainfall.

The M. Steinburg walnut grove lying one mile south of Hemet, Riverside County, California, was chosen for this study. At the beginning of the experiments, in the fall of 1918, this grove was typical of many which had suffered severely from winter injury. The

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grove is composed of seedling Santa Barbara softshell trees planted 44 feet apart each way. The trees were twelve years old in the spring of 1918. This grove received no irrigation until the fall of 1918. The development of a young walnut grove under dry-farm conditions is rather exceptional in the Hemet region, and the lack of irrigation may possibly be the reason why the grove under discussion exhibited an extreme case of winter injury.

The soil is an alluvial fine sandy loam with a low organic content. In general the subsoil is somewhat finer than the surface soil. This change in the fineness of the soil is gradual and perceptible to a depth of 12 feet. A well drilled in the grove soon after the experiment started showed the nearest ground water to be 84 feet from the surface.

CLIMATIC FACTORS AFFECTING SOIL MOISTURE

Rainfall in the Hemet Region, and Penetration of Rain and Irrigation Water

The walnut grove in which the observations were made is located about four miles from a station of the U. S. Weather Bureau at San Jacinto. Records of rainfall kept since 1886 are available and may be used, although the precipitation at the walnut grove is, on account of neighboring topography, possibly less than at the official Weather Bureau Station. The records of rainfall referred to on the following pages were taken one mile from the grove by the Lake Hemet Water Company during the progress of the experiment. The mean seasonal precipitation for the twenty-seven years from 1892–93 to 1918–19, inclusive, is 13.2 inches, with a range of between 7.9 and 18.9 inches The monthly distribution of rainfall is shown in table 1.

TABLE 1

Mean Monthly Rainfall at San Jacinto (Mean of 26 Years)

	Inches		Inches
July	.13	January	2.97
August	.21	February	2.28
September	.17	March	2.71
October	.66	April	1.12
November	1.07	May	.42
December	1.42	June	.03

The mean number of days on which there was precipitation of .01 inch or more at San Jacinto is 37. December had an average of four days on which rain fell, January and March had an average of seven, and February of six.

We may summarize the rainfall situation by saying that the grove under consideration is located in a semi-arid district which receives a mean seasonal rainfall of about 13 inches, most of which usually falls in the months of December, January, February, and March. Irrigation is practiced during the growing season, although this particular grove was not irrigated until the autumn of 1918, at which time the trees were twelve years old.

Evaporating Power of the Air

1. Sunshine.

The duration of sunshine is related to loss of water in at least two important ways, the concomitant effect of heat and the use of water in photosynthesis. The Hemet region is characterized by almost complete freedom from clouds or fog during the growing season, and the ratio of sunshine received to the amount possible is high.

2. Temperature.

This walnut grove is situated in a district characterized by high summer temperatures and a high evaporation rate. The summer temperatures are somewhat higher than those prevailing in the large walnut districts nearer the Pacific coast. Frequent comparisons of temperatures in the grove with those given by the official observer at San Jacinto showed little difference between the two. We may therefore refer to the official thermometric readings at San Jacinto, where observations have been taken for more than sixteen years. Some of the important temperature data are summarized in table 2, which gives monthly and annual averages together with the highest and lowest temperatures recorded in twenty-three years.

These figures show that the prevailing temperatures are in a way characteristic of conditions in southern California, although somewhat higher than those commonly found in other walnut-growing districts. The determination of the 'mean temperature,' either for the month or for the year, is of little importance in this locality because of the characteristically wide ranges of the daily temperatures. We may, therefore, consider the monthly maxima and minima.

The monthly maximum temperatures are rather high throughout the year, especially during the summer months. In June and the three following months the maximum temperatures are 15 to 20° higher than in the coastal regions of southern California. When the temperature rose to 115° in June, 1917 (the highest temperature ever recorded in this region), there was a small amount of burning on the leaves and young growth of walnut trees. Temperatures of 108° and 110° during the summer were frequently recorded by the instruments

TABLE 2

TEMPERATURE DATA FROM UNITED STATES WEATHER BUREAU RECORDS AT SAN JACINTO (IN DEGREES FAHRENHEIT)

Month	Mean temperature	Mean max. temperature	Mean min. temperature	Mean range	Highest temperature	Lowest temperature
January	48.8	65.2	35.8	29.4	90	7
February	52.2	68.0	37.2	30.8	93	19
March	54.9	71.0	40.4	31.6	102	23
April	59.5	77.3	44.7	32.6	101	27
May	63.8	80.0	48.3	31.7	109	32
June	71.4	90.9	53.8	37.1	115	37
July	76.8	96.8	59.2	37.6	111	44
August	76.4	96.6	58.4	38.2	109	43
September	71.6	91.8	53.6	38.2	110	38
October	64.2	82.3	47.2	35.1	103	30
November	56.8	74.4	39.8	34.6	99	21
December	50.3	66.2	34.4	31.8	89	20
Annual	62.2	80.0	46.0	34.0	.....	.....
No. of years observed	27	16	16	16	23	23

kept in this grove in standard U. S. Weather Bureau shelters. These individual high temperatures have little influence on the monthly averages, especially when several years are averaged together. In individual years the monthly averages may be somewhat higher than those given in table 2; for example, in July, 1920, the mean monthly maximum in this orchard was 103.5° F. There was no damage to the trees as a result of this high temperature. The mean minimum temperatures by months are from 30° to 40° below the maxima for the corresponding time. Indeed, the wide ranges in daily temperatures are very characteristic of these semiarid regions. On occasional days the temperature range may be as great as 50° F. This fall of temperature during the night is an important factor in the activity

of all vegetation, especially of arborescent plants, because it gives an opportunity for equilibrium to be reëstablished throughout the tree, after the depletion of water from the transpiring parts during the day. During the hottest part of the day the transpiration may be so rapid from the upper parts of the tree that the water-conducting system is unable to supply enough water to equalize the loss. The lower temperatures during the night, by diminishing the rate of transpiration, are favorable to a more uniform distribution of water throughout the tree.

The data in the last two columns of table 2 show the extremes of temperature which have been registered by the San Jacinto observer over a period of twenty-three years. It is evident that there are days even during the winter when the temperature is high enough to cause rapid evaporation during a few hours each day. Observations reported in another paper[1] showed that these trees do often suffer from desiccation during winters of scanty rainfall. The evaporation through the thin cortical layers of the young twigs is great enough under such conditions to reduce their water content to a serious degree and may result in their death. The injury from this cause is unduly severe if, as often happens, these high temperatures occur simultaneously with periods of low humidity and high wind velocity. The chart on page 12 of the publication cited[1] illustrates a condition which frequently occurs in walnut groves where the amount of water in the soil during the winter is dangerously near the critical point. The walnut trees near the flume which received more irrigation water during the summer suffered least from 'die-back.' The injury was progressively more severe as the distance from the flume increased, because the amount of soil water was progressively less.

3. Humidity.

The Hemet district is characterized by low atmospheric humidity during most of the growing season. Under these conditions there is a rapid loss of water from the soil and trees. While the high evaporating power of the air is conspicuous to the most casual observer, and its effects are quickly noticed, it is difficult to make quantitative measurements of the condition which is commonly expressed by the term 'aridity.'

We know of no determination of the evaporation of water from a free surface in the Hemet district, but we may gain a fairly trust-

worthy idea of its rate from the data published by Russell.[5] His tables show evaporation of 43.3 inches at Sacramento and 56 inches at Fresno during the eight months from April 1 to November 30. If we assume that the evaporation at Hemet is 48 inches for this period, we shall probably not be far wrong. During this period the average rainfall for the Hemet-San Jacinto region is 3.81 inches. Using these

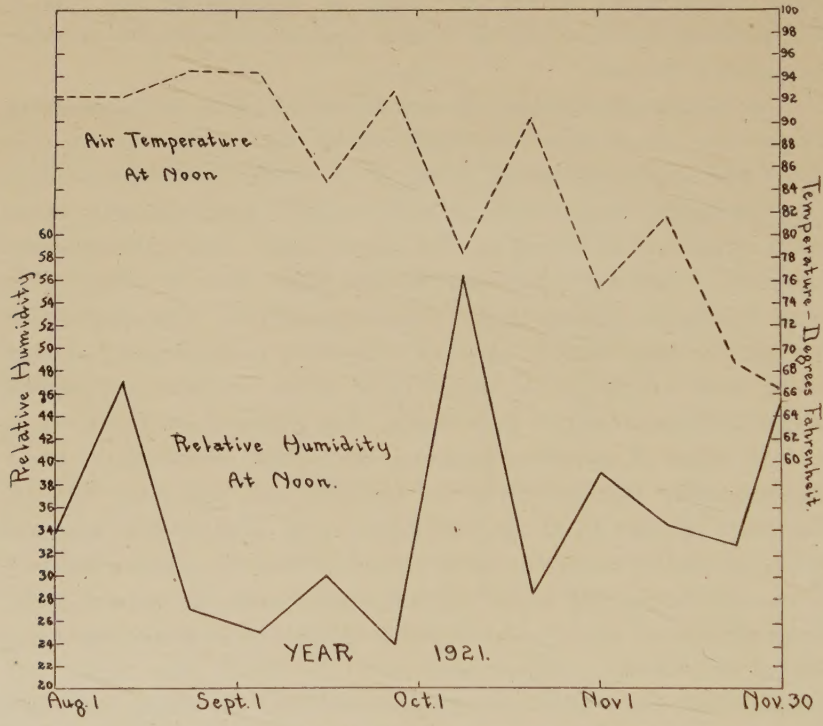

Diagram 1. Relative humidity and temperature at Hemet, August 1 to December 1, 1921.

figures, we see that the ratio of rainfall to evaporation is .08. This period, including two-thirds of the calendar year, is certainly marked by high evaporation and shows one aspect of the climatic conditions which govern plant life in this region.

Determinations of the vapor pressure of the air at Hemet were made during the latter part of the season of 1921 by means of wet and dry bulb thermometers. The determinations are expressed as mean relative humidity for ten-day intervals and are shown in diagram 1. They show that, for most of the season subsequent to

July, the moisture content of the air was very low. The one outstanding exception occurred early in October. It followed a precipitation of 2.95 inches of rain from September 30 to October 2, and was simultaneous with a depression of the mean midday temperature. Another rain on October 23 and 24, which gave a precipitation of .43 inch, also caused an increase in the relative humidity and a fall in mean midday temperature.

These figures give a picture of the evaporating power of the air at a time of the day when evaporation is probably close to the maximum. It is certain that the rate of evaporation during most of the day is much below this figure. During the night the trees have an opportunity to recover from water deficit incurred during the middle of the day.

4. Winds.

Winds in the Hemet region have a well-marked influence upon evaporation. During the summer and fall months there is usually a moderate westerly wind every day. This is the 'coast breeze' which blows from the Pacific Ocean to the hot interior deserts. Although the wind comes from the ocean, its relative humidity is not high, at least by the time it reaches the Hemet district, which is 45 miles from the coast. This daily coastal wind undoubtedly increases the evaporation from both soil and trees.

Evaporation is also increased by irregular east or north winds which come for periods of several days during the fall or early winter months. These winds, coming from the inland deserts, are powerful desiccating agencies. The relative humidity often ranges from 13 to 20 per cent for twenty-four to forty-eight hours at a time, during the prevalence of these northerly winds. Although the trees are partially or wholly bare of leaves at this season, there is nevertheless an appreciable loss of water through the thin bark of the young growth.

Length of Growing Season

The time between the last killing frost in the spring and the first killing frost in the fall, generally designated as the 'frostless season,' corresponds fairly closely with the growing season for walnuts.

The Weather Bureau records show that the average length of the frostless season at San Jacinto for eighteen years is 254 days, with a

minimum of 199 and a maximum of 301 days. For the three years during which our observations were being made in this orchard at Hemet the dates between killing frosts were:

1919, March 21 to November 28	(252 days)
1920, March 27 to December 4	(252 days)
1921, April 6 to November 18	(227 days)

The length of the first two seasons was very nearly the mean, but the last season was considerably shorter.

CONDITION OF TREES AND SOIL AT THE BEGINNING OF THE EXPERIMENTS

The majority of the trees in the several plots (diagram 2) were severely killed back by winter injury during the winter of 1917–18. That the cause of the winter injury in this grove during this season was due to winter drought seems reasonably certain. The first winter rain occurred January 13, 1918, when .43 of an inch fell. The second rain of .25 of an inch occurred on January 25, 1918.

The last rain of 0.3 of an inch or more preceding that of January 13, 1918, fell on April 17, 1917 (with the exception of a thunderstorm on July 27 which gave 1.87 inches). Thus 270 days had elapsed between rains that were of sufficient amount to affect the moisture content of the soil in any great portion of the root zone. The shower in July probably reached a few of the surface roots in the first foot of soil, which was in an air-dried condition previous to the rain. Not until January 26, 1918, did enough rain fall to moisten the surface foot of soil. On this date 1.14 inches of rain fell.

The extreme dryness of the soil in this grove before the winter rains began can be realized when it is recalled that there were twenty-two walnut trees per acre, twelve years old, growing on the land under dry-farm conditions where the normal rainfall of 13 inches comes almost exclusively during the dormant period of the walnut tree. Thus in the absence of rain from July to January 13, the soil-moisture content of the root zone was reduced to a point seldom reached under cultural conditions.

Soil samples were taken October 30, 1917, when the leaves on the trees were turning yellow and a portion of them had fallen. At this

time the surface foot of soil was dust-dry and showed a moisture content of only 0.7 per cent. The condition of the subsoil is shown by the ratio given in table 3.

As mentioned above, such dryness of the subsoil as herein reported is seldom observed under cultural conditions. In fact the results of the preliminary observations were so extreme that it seemed as though an unnoticed error must have occurred in weighing or calculating. Repetitions, however, confirmed these findings.

TABLE 3

THE SOIL MOISTURE AND ITS RELATION TO THE HYGROSCOPIC COEFFICIENT AT THE END OF THE 1917 GROWING SEASON

Depth	Hygroscopic point	Moisture observed	Ratio
	Per cent	Per cent	
2nd foot	2.44	1.31	0.54
3rd foot	2.26	1.74	0.77
4th foot	2.74	2.34	0.85
5th foot	4.30	2.97	0.69

Most of the soil-moisture studies made by previous workers under field conditions have dealt with that portion of the soil moisture which is above the wilting point, because they have not been made under the extremely arid conditions which may be observed in regions like that here described. Alway,[2] however, has reported studies in which the soil moisture was below the hygroscopic point. He gives data upon the soil of an abandoned olive orchard in Arizona, of the prairies of southwestern Nebraska,[3] and of cylinders in which desert legumes had been grown under controlled conditions. Regarding the condition of these perennial desert legumes when the observations were made the author reports, "In none were all the plants dead when the cylinders were opened but in the case of each all the tips had died and nearly all the leaves had fallen, the most vigorous plant in each retaining only from five to seven compound leaves." "In experiments with perennial desert legumes the plants remained alive after the water content had fallen slightly, but distinctly, below the hygroscopic coefficient . . . " Apparently the moisture conditions in the dry-farm walnut grove are similar to those in Alway's cylinders in which desert legumes were grown. As that author has suggested in the case of the desert plants, although there is no evidence of any ability on the

part of the walnut to use the last portion of free water *for growth*, there is an indication that the moisture between the wilting point and the hygroscopic point, and even some of the water below the

Fig. 1. A general view in the Steinburg walnut grove in May, 1918, showing the injury which resulted from a lack of soil moisture during the preceding winter.

hygroscopic point, may have a very high value for the maintenance of the life of the perennial and tree crops.

As heretofore noted, in the spring following the dry winter of 1917 many of the trees were dead in the uppermost branches and some of them killed back nearly to the main scaffold limbs. The distribution of the injured trees in the grove is given in diagram 2, while the nature of the injury on some of the individual trees is shown in figures 1 and 2.

Fig. 2. A badly injured tree in the Steinburg grove, showing how the young branches tend to die back as a result of winter drought.

The grove was dry-farmed during the summer of 1918 which followed a total rainfall of 13.46 inches for the entire rainy season preceding. In the following November the owner installed an irrigation pipe line and the grove was given a light irrigation of 3.6 acre

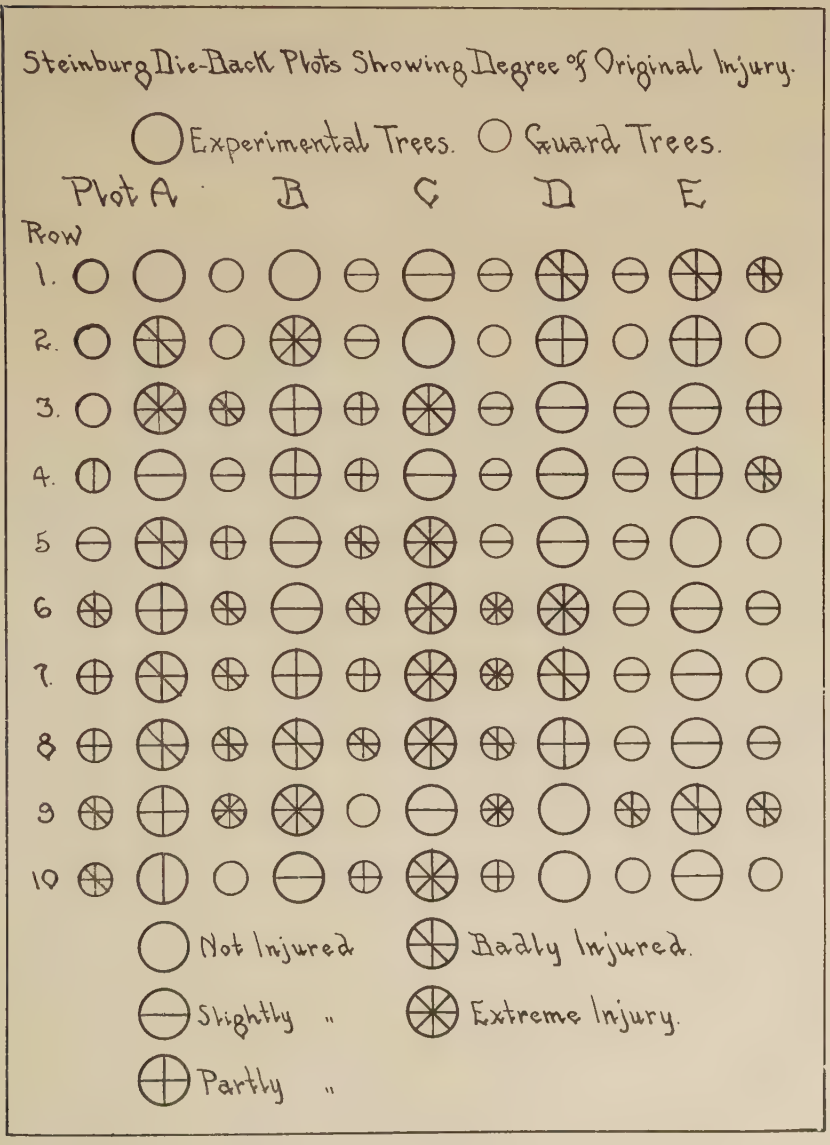

Diagram 2. Distribution of injured trees in Steinburg grove, 1918.

inches per acre, after which it passed under the control of the Citrus Experiment Station and was irrigated as will be described later.

Since the winter of 1917–18 the rainfall has commenced early and has been sufficient in amount to prevent drought injury; thus the seasons have not been favorable to a study of extreme winter drought conditions as related to the growth of winter-irrigated walnuts. This may therefore be a somewhat incomplete report of progress. Inasmuch, however, as the work is to be discontinued on the Steinburg grove and taken up on the Citrus Experiment Station grounds, it seems best to report progress to date.

Diagram 3. Map of a typical plot showing location of irrigation furrows, locations from which samples were taken, and relative positions of experimental and guard trees.

METHODS OF PROCEDURE

Plan of Plots

Each trial plot was laid out to include ten trees in a single row with guard rows between plots. The entire area from guard row to guard row was irrigated, sampled, and in every way regarded as belonging to the adjacent experiment row. See diagram 3.

Irrigation

The irrigation water was measured over a rectangular weir and applied in deep furrows 440 feet long; 8 furrows were used in each interspace of 44 feet, with the lower portion of the plot cross-furrowed. The method of cross-furrowing retarded the velocity of the water and increased its depth in the furrows, thus largely equalizing the amounts of water received by the upper and lower ends of the plots.

Water was applied at the rate of 15 southern California miner's inches (0.3 of a second foot) per acre. This is a larger stream of water per acre than is commonly used in the Hemet–San Jacinto section. Because of the sandy nature of the experimental plots, however, the use of the stream mentioned was in harmony with good irrigation practice.

TABLE 4

IRRIGATION WATER APPLIED TO THE PLOTS (IN ACRE INCHES PER ACRE)

Dates	Plots				
	A	B	C	D	E
1918					
November 8-9	3.6	3.6	3.6	3.6	3.6
December 18	5.7		4.0		9.7
1919					
April 16		1.8			
May 14		1.8			
June 19	4.2	1.8	4.2	4.2	4.2
July 16	4.2	1.8		4.2	4.2
August 13	4.2	1.8	4.2	4.2	4.2
September 17		1.8			
October 15		1.8			
December 11-13	6.6		4.2		9.7
	28.5	16.2	20.2	16.2	35.6
1920					
March 16-17	7.2				
April 20		1.8			
May 18		1.8			
June 15	4.2	1.8	4.2	4.2	4.2
July 20	4.2	1.8		4.2	4.2
August 10	3.2	1.8	4.2	4.2	4.2
September 15		1.8			
October 13		1.8			
November 30	13.1		4.2		9.7
	31.9	12.6	12.6	12.6	22.3
1921					
April 18		1.8			
May 16		1.8			
June 14	4.2	1.8	4.2	4.2	4.2
July 19	4.2	1.8	4.2	4.2	4.2
August 9	4.2	1.8		4.2	4.2
September 13		1.8			
October 11		1.8			
December 13-15	6.3		4.2		6.5
	18.9	12.6	12.6	12.6	19.1

In general the water-holding capacity of this soil gradually increases with the depth. The hygroscopic point of the surface soil varies from 2 to 3 per cent, whereas that of the sixth and seventh foot varies from 3 to 6 per cent. There is one abrupt change in soil type in plot D. The fourth foot in one of the transverse sampling areas consists largely of coarse sand the hygroscopic point of which is only 1.98 per cent.

Since the experiment was installed for the purpose of acquiring information on the relation between soil water and die-back, the amounts of water applied to the several plots and the time of their application were varied. The schedule of applications is given in table 4. It will be seen that this plan of irrigation afforded an admirable opportunity to observe the water content of the soil as affected by the growth of the trees and by the application of different quantities of water. Plots B, C, and D in the last two years received the same total quantity of irrigation water (12.6 inches), the customary amount in the Hemet district, but the time of application was varied in the different cases. Plots A and E were given considerably more water in the winter than the other plots.

So far as the trees are concerned, however, the amount of water in the soil is of more importance than a record of the amount of water applied. Determinations of the amount of water in the soils of the various plots were made before and after each irrigation and at such other times as were judged necessary.

Soil Sampling

As noted in diagram 3 the samples were taken across the upper, middle, and lower end of each plot. At each transverse area samples were taken for each foot separately, down to and including the seventh foot, and each sample consisted of a composite made up of six cores from the soil tube.

A moisture determination was made on each of the composite samples and the three results were averaged to obtain the mean moisture content for each footlevel of the plot.

Method of Expressing Results

1. Soil Moisture Data.

In the following discussion the soil moisture content is stated in the form of a ratio to the hygroscopic coefficient, following the usage of Alway and co-workers,[3] whose comprehensive tables and discussions might well serve as an example to other workers. With a tabulation of the hygroscopic coefficients in tables 7 and 8 preceding the respective ratios, the reader may visualize the type of soil worked with as well as its relative moistness.

We have usually compared our data on the moisture content of the soils with the hygroscopic coefficient rather than the wilting-point coefficient. There seemed to be two good reasons for such a procedure: first, the trees often did not wilt when the soil moisture in the root zone was below the 'wilting point,' and second, the comparisons of moisture content with the wilting point would frequently involve the use of minus quantities.

2. Reliability of the Hygroscopic Coefficient.

The labor involved in sampling the several plots twice per month throughout most of the year made the determination of the moisture equivalent and hence of the hygroscopic coefficient for each respective composite of six cores a practical impossibility. The hygroscopic coefficients here presented are the mean values for a series of six determinations made in the respective areas, each determination representing a composite sample taken entirely independently of every other at an interval of at least thirty days. The determinations for the six respective samples were made by four different people. The personal and time elements, as well as the error in sampling, were therefore somewhat reduced in obtaining this mean as compared with the determination of six samples from the same composite, or of samples from different composites taken by the same person simultaneously. The six determinations may thus be considered as six attempts to measure the same thing, viz., the hygroscopic point of a certain foot section of a given plot.

A statistical inquiry may be profitably applied to these data to test their reliability as compared with the mean of an infinite number of determinations. The tables of 'Student'[6] serve as a ready means of applying statistical methods to this inquiry. As this author so aptly states: "Any experiment may be regarded as forming an indi-

vidual of a population of experiments which might be performed under the same conditions. A series of experiments is a sample drawn from this population.'' With this viewpoint in mind it becomes of interest to determine the reliability of a mean of a series of six determinations of the hygroscopic coefficient. The third foot in plot A in the sampling area nearest the pipe line will serve as a fair example. Following 'Student's' procedure the example works out as follows:

RELIABILITY OF THE MEAN OF THE HYGROSCOPIC COEFFICIENT

V	D	D^2
3.91	.33	.1089
3.80	.22	.0484
3.06	—.52	.2704
3.24	—.34	.1156
3.89	.31	.0961
3.57	—.01	.0001
M = 3.58		6) .6395
		.1066

$$\text{S. D.} = \sqrt{.1066} = .3265$$

The probability that the true mean does not differ from the mean of the sample by more than $\pm .3$ per cent moisture may be found as follows:

$$Z = \frac{.3}{.3265} = .9$$

In Student's tables when $Z = .9$ and $N = 6$, P is .9498. Subtracting, $1.0000 - .9498 = .0502$, which may be taken to mean that the chances are .9498 : .0502 that the true mean does not exceed the mean of the sample by more than .3 per cent moisture.

In our problem, however, we are concerned with a probability that the true mean is just as liable to lie below as above the mean of the sample. Thus we proceed farther to obtain these odds as follows: $.0502 \times 2 = .1004$. Subtracting as before, $1.0000 - .1004 = .8996$. The odds that the true mean does not vary from the mean of the sample by more than $\pm .3$ per cent are .8996 : .1004, or practically 9 to 1.

Although odds of 9 to 1 are not considered a 'reasonable certainty' in statistical studies, such odds do indicate that the use of the mean of the hygroscopic coefficients is probably as reliable within the limits of $\pm .3$ per cent moisture as most comparisons, subject to the error of soil sampling.

RESULTS AND DISCUSSIONS

Penetration of Rain and Irrigation Water

The soil on which this grove is located absorbs water readily, and there is practically no run-off, even during seasons of heavy precipitation. The rate of water penetration is roughly indicated by table 5,

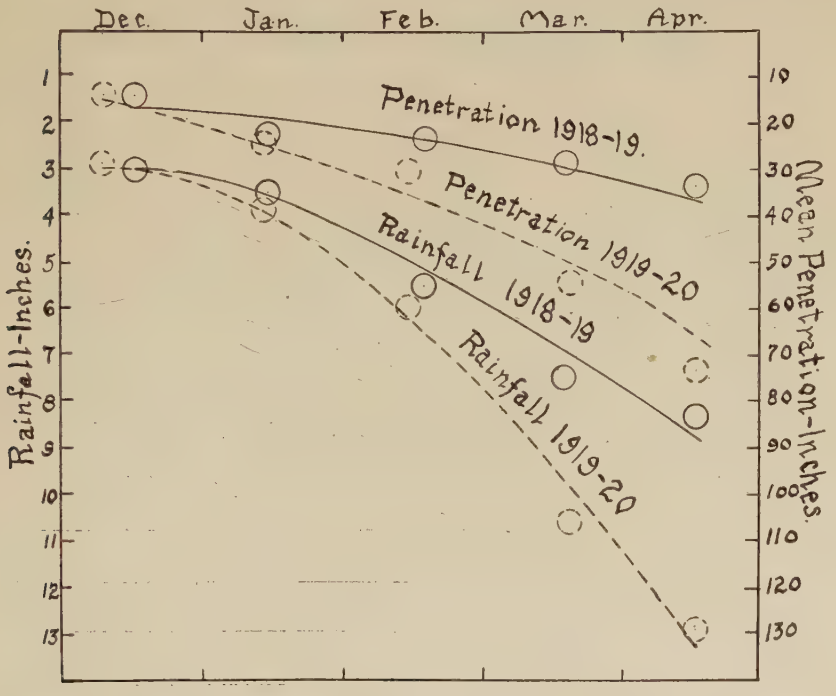

Diagram 4. Relation of rainfall to its penetration in the grove in two seasons.

showing the observations made during the winters of 1918–19 to 1920–21, inclusive. Diagram 4 represents the relation of rainfall to penetration as based on two-years' observation.

The moisture penetrates this soil from 4 to 6 inches for each inch of rain. The factors responsible for this relatively small penetration seem to be: first, the extreme initial dryness of the soil; second, the small amount of rain falling in many individual storms; third, a rate of evaporation between storms so rapid that much of the water passes into the air before another storm occurs.

The penetration of irrigation water may be illustrated by plot A as observed during the winter of 1919–20. The rain to December 9 was 2.87 inches and it had penetrated 10 inches on plot A. The plot was then irrigated with 6.56 acre inches per acre, and 8 days later the moisture penetration in 18 holes averaged 54 inches. The soil moisture had been lowered, therefore, 6.7 inches per acre inch of water applied. This is somewhat less penetration than Harding[4]

TABLE 5

RAINFALL AND DEPTH OF PENETRATION IN PLOTS B AND D (IN INCHES)

1918-1919

Date	Dec. 16	Jan. 15	Feb. 17	Mar. 18	April 16	Average penetration per inch of rainfall
Rainfall to date	2.99	3.45	5.46	7.47	8.25	
Penetration in dry plots	*14*	*22*	*23*	*28*	*33*	*4.0*
		1919–1920				
Date	Dec. 9	Jan. 13	Feb. 18	Mar. 18	April 19	
Rainfall to date	2.87	3.91	5.96	10.58	12.88	
Penetration in dry plots	*10*	*24*	*30*	*58*	*73*	*5.7*
		1920–1921				
Date	Dec. 15		Feb. 2	Mar. 8	April 18	
Rainfall to date	1.63	.....	4.60	5.12	6.20	
Penetration in dry plots	*18*	.....	*24*	*25*	*37*	*5.9*

Mean *5.2*

reports for a similar amount of water. Harding, however, was dealing with movement of soil moisture under ordinary irrigation practice where the content seldom drops below the wilting point, whereas we are considering the winter irrigation of a soil in which the initial soil moisture was close to the hygroscopic point 120 days after the last irrigation.

The summer irrigation which was given at a time when the moisture was close to the wilting point penetrated deeper and harmonizes

more closely with Harding's observations. This is best illustrated by plots A and C following August irrigation of 1920. Table 6 shows the amount of water applied, the relative dryness of the soil before irrigation and the average penetration per acre inch of water. In plot A, with the moisture of the first 60 inches of soil considerably above the wilting point, the average penetration of 3.18 acre inches of water was 55.9 inches or 17.6 inches per acre inch of irrigation water. Pot C, which was much dryer and in fact had a moisture content nearer the hygroscopic point than the wilting point, after an irrigation of 4.2 acre inches, showed an average penetration of 43.3 inches or 10.3 inches per acre inch of irrigation water.

TABLE 6

DEPTH OF PENETRATION OF IRRIGATION WATER ON PLOTS A AND C, AUGUST, 1920

Plot	Water applied	Soil moisture before irrigation (upper 60 inches)	Average penetration per acre inch
	Acre inches* per acre	Ratio to hygroscopic point	Inches
A	3.18	1.66	17.6
C	4.20	1.17	10.3

* Amount of water accounted for by rise in moisture content of soil 10 days after irrigation.
A 2.128 acre inches per acre.
C 2.641 acre inches per acre.

It may be instructive to examine the records of plot A and to note how the applications of water affected the moisture content of the soil to the depth of 7 feet. Diagram 5 represents graphically the per cent of water in the soil in one-foot sections from December, 1919, to the end of October, 1920, expressing the water as a per cent of the weight of dry soil. Between August 1 and December 1, the precipitation amounted to 1.84 inches at Hemet, but it had fallen in scattering showers and had not appreciably affected the water content of the soil below the first foot. At the beginning of the observations the soil moisture below the first foot was very close to the hygroscopic coefficient. After the irrigation of 6.6 inches on December 11–13 there was a perceptible increase in the water content of the second, third, fourth, and fifth foot layers of soil, as determined from samples taken six days after irrigation. At the time the soil was next sampled, in March, the water content of the deeper layers had

increased to about the same per cent as that of the upper layers. This was due both to the steady downward movement of water and to the addition of 6.56 inches of rain after January 1. The heavy irrigation (7.2 inches) given on March 16 and 17 appreciably raised the water content of the deeper layers of the soil and to a less extent of the

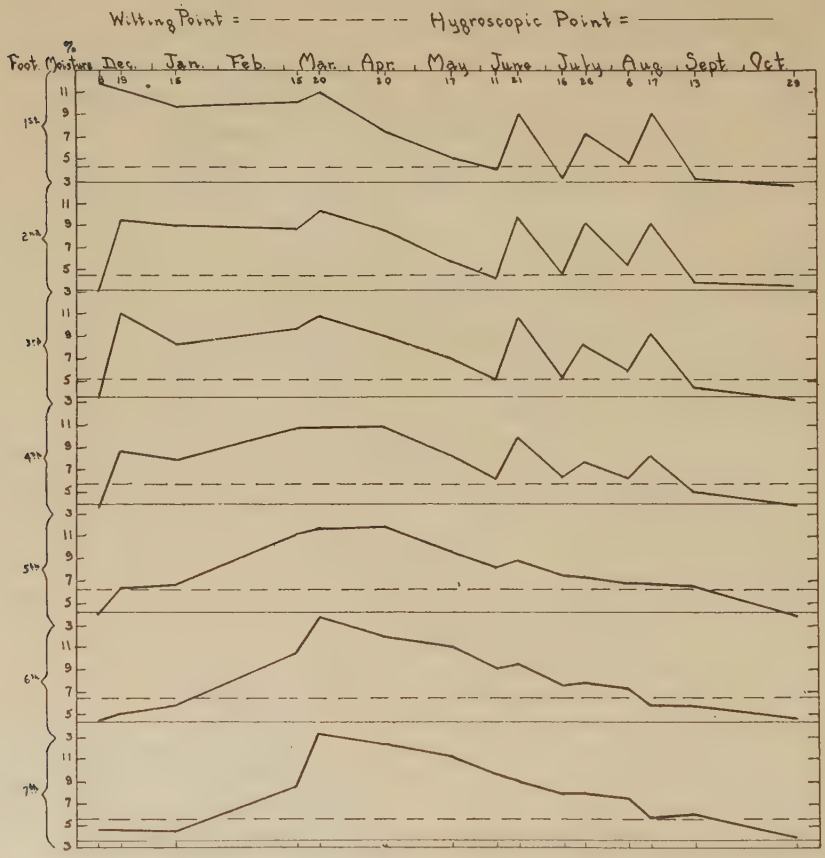

Diagram 5. Seasonal variations in moisture content of the upper seven feet of soil in plot A from December, 1919, to October, 1920. The horizontal line represents the mean hygroscopic coefficient of the samples at each level, and the broken line represents their wilting point coefficient.

surface layers. After a precipitation of .93 inches on March 23 there were no more rains of consequence and the soil water content steadily diminished until the next irrigation, owing to the removal of water by the trees during the period of rapid growth characteristic of spring and early summer. When sampled on June 10, the soil water of the

first four foot-layers was practically at the wilting point. In other words, the trees had removed practically all of the water 'for growth' from the zones in which most of the active roots are located. The application of 4.2 inches of irrigation water in June and July, and of 3.2 inches in August temporarily raised the water content of the first four foot-layers of soil, but made little difference in the water content of the lower layers.

The depth of penetration of like amounts of irrigation water varied from year to year according to the rainfall. This can be readily understood by noting the rainfall penetration shown in diagram 4.

Effect of Irrigation on Soil Moisture

The relation of soil moisture during the winter months to the need of irrigation the following summer or the following growing season is of both practical and scientific interest. Table 7 gives the moisture present in plots A and D from March, 1920, at monthly intervals until October. Both plots received practically the same irrigation during June, July, and August. Plot A received winter irrigation of 13.8 acre inches per acre, while plot D was not winter-irrigated. The winter rains amounted to 13.74 inches and penetrated 73 inches on plot D. Although plot A showed a considerably greater amount of soil moisture at the beginning of the growing season, there was no significant difference in the two plots by the middle of July. This table and table 8 show that there is no 'hold-over' of soil moisture from one season to another in the zone of greatest root development. It may also be concluded from this table that the effect of heavy winter irrigation will not persist beyond the middle of the growing season under the condition in this orchard. From this time until the beginning of the dormant period, the irrigation needs are the same as though no winter water had been applied. This may not apply to the subsoil where relatively few roots are developed, a depth from 8 to 20 feet from the surface, provided any of the irrigation water reaches such depths; the rainfall seldom reaches a depth of more than 4 or 5 feet in the district in question. Slight irregularities had gradually developed in plots A and D when the data in table 7 were taken. Since the former plot had been heavily winter-irrigated for the two years previous, the trees had grown somewhat larger and no doubt made somewhat greater demands on the soil moisture than those in plot D.

TABLE 7

COMPARISON OF SOIL MOISTURE IN PLOT A RECEIVING HEAVY WINTER IRRIGATION OF 13.8 ACRE INCHES PER ACRE AND PLOT D WHICH WAS NOT WINTER-IRRIGATED IN 1919–1920

Soil moisture expressed as a ratio of the hygroscopic point

Ft.	Hygro. point		March			June			July			August			September			October		
	A	D	A	D	Dif.	A	D	Dif.	A	D	Dif.	A	D	Dif.	A	D	Dif.	A	D	Dif.
1	3.05	2.45	3.67	3.30	0.37	1.39	1.08	0.31	1.11	0.94	0.17	1.61	1.45	0.16	1.12	0.96	0.16	0.92	1.11	−0.19
2	3.17	2.43	3.41	3.08	0.33	1.40	1.34	0.06	1.47	1.66	−0.19	1.74	1.87	−0.13	1.24	1.37	−0.13	1.12	0.95	0.17
3	3.61	2.83	3.05	3.17	−0.12	1.43	1.71	−0.28	1.50	1.72	−0.22	1.67	1.91	−0.24	1.26	1.51	−0.25	0.94	1.08	−0.14
4	3.97	2.77	2.78	3.17	−0.39	1.57	1.55	0.02	1.61	1.88	−0.27	1.64	2.08	−0.44	1.28	1.52	−0.24	0.95	1.09	−0.14
5	4.21	4.56	2.80	2.40	0.40	1.95	1.63	0.32	1.78	1.63	0.15	1.64	1.78	−0.14	1.34	1.46	−0.12	0.92	1.02	−0.10
6	4.42	5.71	3.12	1.80	1.32	2.08	1.69	0.39	1.76	1.88	−0.12	1.69	1.83	−0.14	1.30	1.58	−0.28	1.06	1.07	−0.01
7	3.79	5.32	3.53	1.61	1.92	2.56	1.78	0.78	2.13	2.13	0.00	2.02	1.93	0.09	1.64	1.70	−0.06	1.03	1.33	−0.30
Mean	3.75	3.72	3.19	2.62	0.55	1.77	1.54	0.23	1.62	1.69	−0.07	1.72	1.84	−0.12	1.31	1.44	−0.13	0.99	1.09	−0.10

TABLE 8

SOIL MOISTURE IN THREE PLOTS EXPRESSED AS A RATIO OF THE HYGROSCOPIC POINT

(The hygroscopic points stated below are the means of six different sets of samples and determinations for the respective foot-samples.)

Depth of foot-section		Plot A Soil moisture				Plot B Soil moisture				Plot C Soil moisture			
		Hygro. Point	Oct. 1919	Oct. 1920	Sept. 1921	Hygro. Point	Oct. 1919	Oct. 1920	Sept. 1921	Hygro. Point	Oct. 1919	Oct. 1920	Sept. 1921
Upper portion of plot	1	2.79	0.76	0.83	1.18	2.43	1.20	2.00	1.50	2.11	1.42	1.13	0.99
	2	2.98	1.03	1.15	0.92	2.77	0.88	1.78	1.09	2.39	1.04	1.03	0.94
	3	3.58	0.99	0.99	0.92	2.71	1.04	1.59	1.62	2.33	1.14	1.25	1.11
	4	4.09	1.06	1.01	0.90	3.39	.....	1.33	1.23	2.69	0.90	1.38	1.36
	5	4.08	1.08	0.81	0.97	3.67	0.95	1.05	1.00	4.88	0.88	1.14	0.95
	6	3.85	1.02	1.05	0.98	3.38	1.15	1.32	1.17	6.42	0.98	1.06	1.06
	7	3.69	1.08	1.02	1.00	3.09	1.09	1.05	1.32	4.87	0.93	1.45	1.19
Middle portion of plot	1	2.85	0.46	1.15	0.95	2.52	0.61	1.50	1.11	2.52	1.23	0.76	0.46
	2	2.86	0.88	1.24	1.13	2.56	1.09	1.27	1.38	2.44	0.94	0.98	0.96
	3	3.25	1.06	1.17	1.12	3.05	1.06	1.10	1.22	2.26	0.99	1.10	0.91
	4	3.50	1.06	1.15	0.99	4.08	0.98	1.07	1.22	2.74	0.85	1.07	1.22
	5	3.97	1.06	1.05	1.08	4.24	0.92	1.00	1.07	4.30	0.92	1.04	0.97
	6	4.30	0.95	1.13	1.08	3.72	1.01	1.04	1.15	4.41	0.92	1.15	1.11
	7	3.46	1.10	1.21	1.25	3.88	0.80	1.03	1.13	3.35	1.12	1.79	1.11
Lower portion of plot	1	3.52	0.81	0.96	0.61	2.92	1.22	1.23	0.70	2.51	1.19	0.98	0.72
	2	3.67	0.88	1.45	0.88	3.04	0.89	1.03	1.26	2.60	0.94	0.90	0.83
	3	3.99	0.98	0.94	0.89	3.39	1.23	1.06	1.14	3.01	0.91	1.01	0.99
	4	4.31	0.97	1.01	0.91	4.28	1.14	1.09	0.81	4.48	0.95	1.03	0.85
	5	4.58	1.02	1.00	1.02	4.59	1.10	1.03	0.93	5.52	0.89	0.99	0.82
	6	5.10	1.12	1.06	0.98	4.88	1.07	0.96	0.99	3.68	1.03	1.23	0.98
	7	4.23	1.25	1.12	0.94	4.48	0.86	0.91	0.83	2.95	1.05	1.33	1.03
Mean			0.98	1.07	0.99		1.01	1.21	1.14		1.01	1.13	0.98

The percentage of water in the soil of plot A and its variations during the growing season are given in diagram 5. The water content of each of the upper seven feet of soil is stated in relation to the wilting and the hygroscopic coefficients. The diagrams show how the water content of soil lying at various depths is influenced by additions of water. The upper layers of soil respond more quickly to a fall of rain or to an application of irrigation water, but also lose their water more quickly. The loss of water during the summer months is principally due to the absorbing action of the tree roots, which are more densely distributed in the upper four feet of soil in this grove. It will be noted that the water content of each foot-layer except the first was below the wilting point on December 5, 1919; indeed, with the exception of the first and seventh, all were below the hygroscopic point. As the result of an irrigation of 6.6 acre inches per acre, the moisture content of the second, third, and fourth foot-layers rose sharply, but the fifth, sixth, and seventh foot-layers were not raised above the wilting point.

As a result of the winter rains and of another irrigation of 7.2 acre inches the water content of the various layers was much higher when sampled March 31, 1920. The increase was especially marked in the case of the first and the seventh foot-layers. Subsequent samples taken April 19, May 17, and June 11 showed a steady decline in water content. The trees put out new foliage and began active growth the last week in March.

The samples taken on June 11 showed that the water of the layers of soil occupied by most of the tree roots had fallen approximately to the wilting point. Irrigations of 4.2 acre inches per acre in June, July, and of 3.2 in August, materially raised the water content for a brief time, but within thirty days it dropped back to the approximate value of the wilting point. During the entire summer the water content of the fifth, sixth, and seventh foot-layers declined almost continuously, showing but little response to the irrigation water applied. No water was applied to this plot in September or October. When the plot was sampled on October 29, the soil at all levels in the upper seven feet was approximately at the hygroscopic point.

These observations show that in this grove the stored soil moisture from heavy winter rains or irrigation is of importance in the upper root zone only up to the middle of the growing season. The effect of

such moisture may persist in the subsoil where fewer roots are developed, until well past the middle of the growing season. They also show the failure of ordinary medium applications of irrigation water (4.6 acre inches per acre) to maintain the soil moisture during the late summer months.

Desiccation of the Soil by Tree Roots

The dryness to which the soil is reduced* at the end of each growing season is of vital interest in connection with the possible winter-injury of the trees due to desiccation during seasons of light rainfall.

The soil moisture present at the commencement of the dormant period of the trees is generally very small. Under the conditions which usually prevail, the last irrigation is applied late in August† just before the nuts ripen. The fall and early winter rains have come too early during the years 1919–1921, inclusive, to permit the study of the effect of a winter drought such as occurred in the two years before the irrigation experiment began. The studies here reported are therefore not conclusive proof of the effect of winter drought on walnut trees, but rather indicate the extreme dryness to which the soil is reduced at the commencement of the annual dormant period of the trees. When sufficient rain falls early in the dormant period the trees show no injury from autumn drought. Table 8 shows the moisture content of plots A, B, and C during the falls of 1919, 1920, and 1921.

It is apparent from this table and the discussion in a subsequent paragraph that the wilting point of the soil has no significance for the use of soil moisture by the walnut tree. The hygroscopic point is the critical point at which growth stops and the point at which the tree matures in a perfectly healthy and normal condition. Although this conclusion may not harmonize with many of the soil-moisture studies where annual crops have been used as indicators, it does agree with Alway's studies heretofore mentioned.

The continued dryness of the soil (at the hygroscopic point or below) throughout most of the root zone, is thus a matter of course

* The soil moisture content in the following discussion is stated as a ratio to the hygroscopic coefficient.

† The statement above applies to the irrigation practice in the majority of the walnut-growing sections. In the Hemet region most of the walnut groves are irrigated according to the schedule shown for plot B, on page 13.

during winter seasons of scanty rainfall. The same effect is produced in walnut groves in which is growing a winter barley crop which uses the moisture soon after it falls and thus prevents it from reaching the subsoil. Many observations made in barley fields during the winter of 1918–19 showed that 18 to 24 inches was the maximum depth which the rainfall reached, because, with the light occasional rains and the demands of the barley plants, there was no moisture left for deep penetration. During seasons of normal rainfall walnut trees are frequently severely injured by winter drought if intercropped with barley.

During the progress of this experiment a few cases of winter injury due apparently to drought have come to the attention of the authors. These have all occurred in intercropped orchards. Some have occurred in central California and it has been impossible to obtain any knowledge of the soil-moisture conditions which prevailed before the winter rains and the occurrence of the injury. These survey studies have still further strengthened the conclusions reported by the authors in 1919.[1]

Table 9 shows that in two young orchards, one of apricot and one of peach, on Placentia sandy loam, the latter underlain by impervious hardpan, the moisture content had been reduced below the hygroscopic point. The soil samples were taken December 1, 1921, 113 days after the last irrigation. A light shower occurred in October but it affected only the surface of the soil. The trees in these orchards were apparently entering a normal dormant period on December 1. The following spring (1922) these apricot and peach trees bloomed and started their normal spring growth, which would indicate that the olive and the walnut may not be exceptional in their ability to reduce the soil moisture to the hygroscopic point at the approach of their normal dormant period.

This condition may be considered common in fruit orchards in the semi-arid sections where the rains mainly occur during the dormant period. The reduction of the soil moisture to the hygroscopic point by tree roots apparently is not accompanied by a marked harmful effect, provided it is not prolonged too far into the winter period. It seems quite probable that the soil moisture between the wilting point and the hygroscopic point is of vital importance for maintenance of life and the ripening processes of tree growth.

Fall Growth of Walnut Trees in Relation to Differences in Soil Moisture

The length of the growing season of the walnut tree may be somewhat prolonged in the late summer and early fall by the presence of an abundance of soil moisture, and, vice versa, it may be shortened by a lack of sufficient soil moisture. The effect of late irrigation in prolonging the growth of the trees has been so often observed that it need not be dwelt upon at length in this paper; suffice it to say that it is often associated with injury to the trees by the first fall frosts, and for this reason alone the late irrigation of young walnut trees is inadvisable.

TABLE 9

Soil Moisture in Peach and Apricot Orchards

Three-year-old peach orchard, December 1, 1921. (Trees nearly dormant, three-quarters defoliated.)

Ft.	Hygroscopic coefficient	Moisture observed	Ratio
1	4.91	2.98	0.61
2	5.42	4.81	0.89
3	6.16	5.84	0.95
Mean			0.82

Six-year-old apricot orchard, December 1, 1921. (Trees partly dormant, one-half defoliated, leaves yellowish green.)

Ft.	Hygroscopic coefficient	Moisture observed	Ratio
2	4.96	3.82	0.77
2	5.86	4.61	0.79
2	5.33	4.37	0.82
2	5.84	4.70	0.80
2	4.85	4.26	0.88
2	5.69	4.38	0.77
2	5.58	4.80	0.86
2	5.61	4.78	0.85
2	5.16	4.48	0.87
2	4.42	4.38	0.99
2	4.88	4.71	0.97
2	5.08	4.85	0.96
Mean			0.86

It has been of especial interest in this investigation to determine the dryness of the soil necessary to entirely check the growth of the tree and thus promote the commencement of the dormant period. The year 1921 was favorable for this sort of observation, inasmuch as the preceding winter rains were below the average and penetrated to a depth of only about 37 inches. With the addition of water from winter irrigation (see table 4) the depth of moist soil on plots A and C was not more than 6 feet. The water level in this grove is about 80 feet from the surface, and the soil below the reach of the rains or irrigation is constantly at a point of extreme dryness. Thus the lower root zone may remain at the hygroscopic point or slightly below this point for twelve to eighteen months at a time during seasons of scanty rainfall. Since summer irrigation did not penetrate more than 7 feet, it is reasonably certain that there was no soil moisture above the hygroscopic point in the lower root zone of the plots in question during the entire growing season of 1921. The greatest amount of water applied at any one time was 4.2 acre inches per acre, with twenty days as the shortest interval between irrigations.

Plots A and C were irrigated for the last time on August 9 and July 19, respectively. On September 13 it was noted that the trees on plot C were maturing somewhat faster than those on plot A. The foliage of the trees of plot C was beginning to turn yellowish green, especially the leaves in the centers of the trees, and a few leaves were beginning to collect on the ground. At the same time the foliage of the trees on plot A was still green. The twig growth had terminated on both groups of trees. None of the trees appeared wilted, although the maximum temperature at 2 P.M. was 85° F.; the relative humidity was 35 per cent, and the soil moisture was reduced to practically the hygroscopic point as shown in table 10.

The above observation was made 34 days after A was irrigated and 54 days after C was irrigated, both plots receiving 4.2 acre inches per acre. Since the same degree of dryness of the soil had been reached in the two plots, the difference in maturity of the trees may be taken to indicate that a prolonged period with the soil moisture between the wilting point and the hygroscopic point is necessary to check the growth of the walnut tree during the warm months of early fall.

The statement is made in a preceding paragraph that, "the soil below the reach of the rains or irrigation is constantly at a point of

extreme dryness.'' It is of interest at this point to note observations which were made in this regard on November 17, 1922. A hole was bored 20 feet deep with a post hole auger, and each foot-level was kept separate for moisture observations. The following summary shows the relative moistness of the soil.

Foot-level	Hygroscopic point	Ratio of moisture observed to hygroscopic point
1	3.2	2.9
2	3.0	1.4
3	3.6	0.9
4	4.2	0.9
5	4.7	0.9
6	4.9	0.9
7	5.5	0.7
8	3.1	1.1
9	2.6	1.1
10	4.3	0.9
11	2.8	0.8
12	1.7	1.5
13	2.6	1.2
14	1.3	1.1
15	5.4	1.1
16	6.8	1.0
17	4.2	1.3
18	5.9	0.9
19	4.8	0.9
20	4.4	0.9
Mean (eliminating 1st foot)	4.0	1.0

Except for the surface foot which had been wet by recent rains, and a sand layer in the twelfth foot, the moisture was very close to the hygroscopic point or below it.

TABLE 10

SUMMARY OF THE SOIL-MOISTURE OBSERVATIONS FOR PLOTS A AND C, SEPTEMBER 13, 1921, EXPRESSED AS A RATIO OF THE HYGROSCOPIC POINT

	Plot A	Plot C
Average of 1st ft.	0.91	0.72
Average of 2nd ft.	0.98	0.91
Average of 3rd ft.	0.98	1.00
Average of 4th ft.	0.93	1.14
Average of 5th ft.	1.02	0.91
Average of 6th ft.	1.01	1.05
Average of 7th ft.	1.06	1.11
Mean	0.98	0.98

SUMMARY

1. The rainfall of the Hemet Valley is less effective in raising the soil-moisture content of the subsoil than might be thought from a mere statement of total rainfall. Much of the rain falls in small showers of only a few tenths of an inch and is rapidly lost by surface evaporation. For a three-year period the total depth of penetration of moisture averaged 5.2 inches per inch of rainfall during the rainy season.

2. Studies made upon the moisture content of the soil in a walnut grove have shown that at the end of the growing season the moisture was reduced to a point near the hygroscopic coefficient, in spite of summer irrigations totaling 12.5 acre inches for the season. After a period of 169 days without a rain of .3 of an inch or more the moisture in the upper five feet of this soil varied from .54 to .85 of the hygroscopic coefficient. The moisture content of a different type of soil in a three-year-old peach orchard and in a six-year-old apricot orchard showed a similar degree of dryness at the same state in the growth cycle of the trees. The average moisture content in the upper three feet of the former soil was .82 of the hygroscopic coefficient, and in the second foot of the latter was .86 of the hygroscopic coefficient.

3. In spite of the low moisture content of the soil in the latter part of the growing season, the trees showed no permanent wilting but continued to mature and entered the dormant period without apparent injury. Temporary wilting occurred only during the middle of the day when a high temperature was accompanied by a low humidity.

4. The moisture content of the soil was generally at the hygroscopic point at the end of the growing season whatever the amount of water present at the beginning. In other words there was no residuum of water for the use of the trees in the following season.

5. The moisture content of the upper seven feet of the soil in this grove gradually increased with the winter rainfall and usually reached a maximum percentage in March, when the moisture present equaled from 2.5 to 3.5 times the hygroscopic coefficient. Early in April the amount of soil moisture was reduced as the trees started their spring growth. The soil moisture of the upper four feet was approximately at the wilting point by the middle of June. The residual moisture from heavy winter irrigation persisted in the subsoil area until the

middle of the growing season, but by the end it had been gradually taken out of this area, where the tree roots are less numerous. Summer irrigations of 4.2 acre inches per acre raised the water content for a brief time, but within thirty days it dropped back to the approximate value of the wilting point. Such irrigation had little effect on the water content of the soil below the fourth foot. By the end of October the soil in the upper seven feet was approximately at the hygroscopic point.

6. In stating the moisture content of the soil in relation to any of the various conventional coefficients, such as the moisture equivalent, the wilting point, or the hygroscopic coefficient, the field studies with walnuts have shown that the hygroscopic coefficient is the most logical point upon which to base all calculations. If the actual moisture present is stated in comparison with the wilting point, for example, we shall be dealing with minus quantities much of the time. It has seemed to the authors that statement of the moisture in a soil as a ratio of the hygroscopic coefficient gives the most comprehensive conception of the relative moistness. When such a ratio is accompanied by a statement of the hygroscopic coefficient, the type of soil worked with can be clearly understood by the reader.

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